Radiation Effects in CdZnTe Gamma-Ray Detectors Produced by 199 MeV Protons

Larry S. Varnell and William A. Mahoney, Jet Propulsion Lab, Pasadena, CA 91109

Ethan L. Hull, Indiana University Cyclotron Facility, Bloomington, IN 47408

Jack F. Butler, Digirad, San Diego, CA 92121

Ah San Wong, Space Radiation Lab, Caltech, Pasadena, CA 91125

ABSTRACT

Many future space missions will use Cadmium Zinc Telluride (CdZnTe) gamma-ray detectors because their operation at room temperature makes compact, lightweight detector systems possible. Even though instruments for space using CdZnTe detectors have already been built, the effect of the high-energy particle space environment on these detectors has not been measured. To determine the effect of energetic charged particles on these detectors, we have bombarded several CdZnTe detectors with 199 MeV protons at the Indiana University Cyclotron Facility. Planar detectors of area 1 cm^2 and thickness 2-3 mm from both eV Products and Digirad were irradiated, along with a 2 x 2 array of proprietary design from Digirad. Using standard gamma-ray sources, the response of the detectors was measured before and after bombardment in steps up to fluences of 5×10^9 p cm^{-2}. Significant effects from the proton irradiation were observed in the gamma-ray spectra. In particular, the peak positions of the lines in the spectrum were shifted downward proportional to the fluence. The explanation is almost certainly the production of electron traps by the high energy proton interactions, resulting in a decrease of the mobility-lifetime ($\mu\tau$) product of the electrons. Calculations were made to model the effect of a decrease in electron trapping length on the spectrum.

Keywords:

Radiation damage, gamma-ray astronomy, CdZnTe, gamma-ray detectors

INTRODUCTION

Solid state gamma-ray detectors are known to suffer radiation damage when flown in space. For example[1], conventional electrode coaxial Ge detectors show resolution degradation from protons with energy above 100 MeV at a fluence of approximately 2×10^7 p cm^{-2}. Reverse electrode Ge detectors are more resistant to radiation effects; in accelerator experiments with high-energy protons, the energy resolution begins to degrade at fluences of a few x 10^8 p cm^{-2} for detectors cooled to 90 K. At higher temperatures, degradation begins at a lower fluence[2].

CdZnTe detectors were proposed for several instruments in NASA's mid-sized Explorer program, including the Energetic X-ray Imaging Survey Telescope (EXIST)[3]. There was little information on the behavior of these detectors in a space environment which, for the proposed EXIST orbit of 500 km altitude and 30° inclination, was expected to be a proton flux above 100 MeV of 1×10^9 p cm^{-2} y^{-1} . To be able to predict their behavior on this mission, several CdZnTe detectors were irradiated at the Indiana University Cyclotron Facility at proton energies typical of those expected in space. The fluence levels for the irradiation

0-8194-2194-4/96/$6.00

experiment were chosen to begin well below the levels where damage could be expected, then increasing to the point where damage would be observed. Based on experiments with Ge and Si detectors, radiation can produce changes in detector leakage current, and in peak position, energy resolution, and efficiency.

Several detectors were used in the experiments. Two planar detectors were purchased from eV Products; one 10 x 10 x 3 mm^3, one 10 x 10 x 2 mm^3. Two detectors were furnished by Digirad; a 10 x 10 x 2 mm^3 planar, and a 2 x 2 array 3 mm thick with each pixel 3 x 3 mm^2. A summary of the detector characteristics is given in Table 1.

Table 1. Characteristics of CdZnTe Detectors used for Irradiation Experiments

Detector	Bias Voltage (V)	Leakage Current (nA)	Resolution at 122 keV (keV FWHM)	Pulser Resolution (keV FWHM)
eV 3 mm	300	12	3.4	2.4
eV 2 mm	200	17	5.6	2.4
Digirad 2 mm	150	7	7.2	3.0
Digirad Array	500	14		
A			5.5	2.6
B			5.7	2.6
C			4.9	2.6
D			5.7	2.6

The preamplifier used was eV Products model 550-5093. An Ortec 572 amplifier was used, with best resolution obtained at 0.5 microseconds shaping time. A Keithley 237 High Voltage Source Measurement Unit was used to supply bias voltage and to measure the leakage current. The detectors were operated in a brass test fixture purchased from eV Products. Bias voltage was applied through a BNC connector which also served as the input to the preamplifier (AC coupled). The fixture had a thin beryllium window which allowed the spectrum to range down to a few keV. The detectors were operated with the gamma rays incident on the negative electrode to minimize the effects of hole trapping. All spectra were taken and all irradiations were carried out with the detectors at room temperature.

The detectors were characterized before the irradiation using calibrated sources of ^{241}Am and ^{57}Co. At several bias voltages, the leakage current was measured, and the peak position, resolution, and FEP efficiency for each gamma-ray line was determined. For the 122.1 keV line, the measured FEP efficiency of the planar detectors is about 25% of that calculated from the photon absorption coefficients. This discrepancy arises from the low mobility and short trapping length for the holes. In some events, holes are trapped before reaching the cathode and the resulting charge pulse is less than full energy. In other events the holes reach the cathode, but the travel time is longer than the 0.5 microseconds shaping time of the amplifier and ballistic deficit results in a pulse less than full energy. These events form the large feature seen from 20 keV to 110 keV in the ^{57}Co spectrum of a planar, such as the 3 mm eV detector shown in Figure 1. By using a proprietary design, Digirad has been able eliminate this feature and increase the number of counts in the peak, as shown in Figure 2.

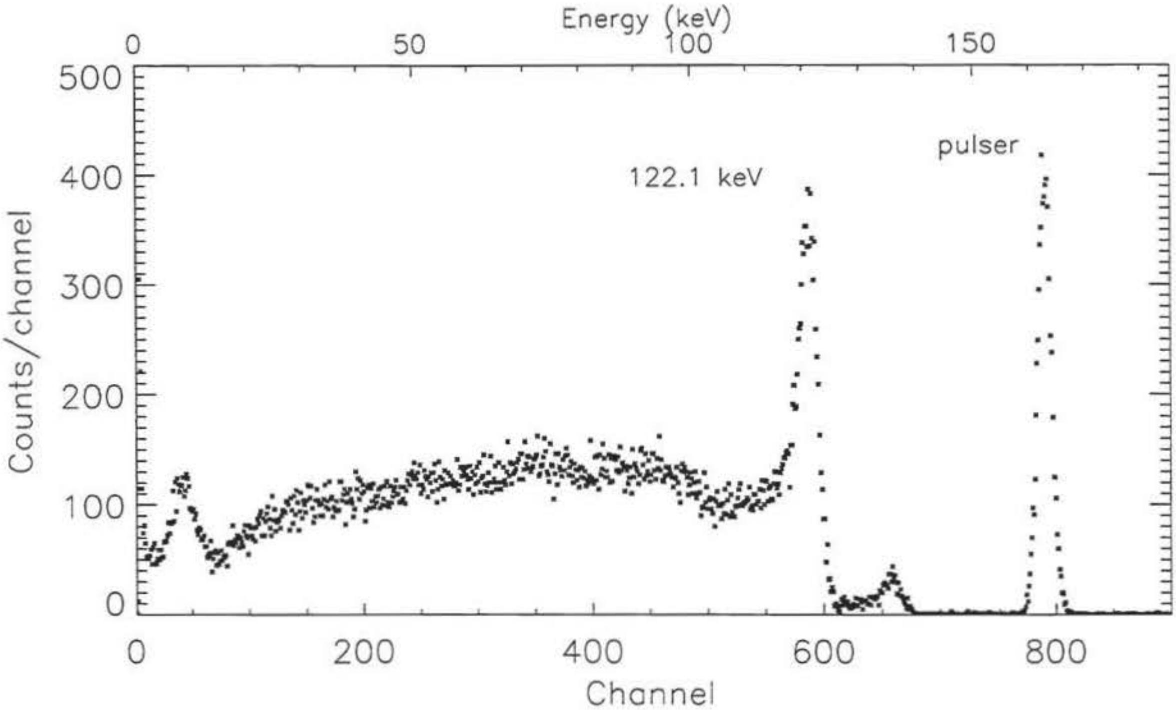

Figure 1. The spectrum of ^{57}Co taken with the 3 mm eV detector.

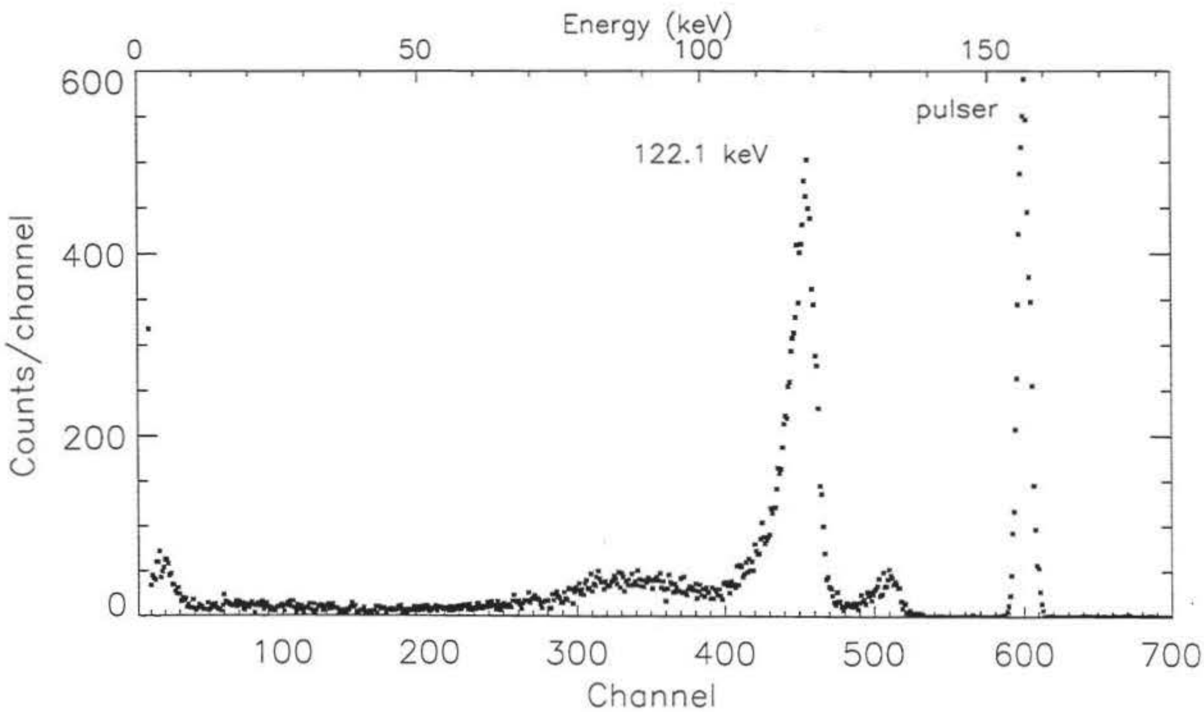

Figure 2. The spectrum of ^{57}Co taken with one element of the Digirad array.

PROTON IRRADIATION EXPERIMENTS AND ANALYSIS

The irradiation experiments were performed with 199 MeV protons from the Indiana University Cyclotron Facility (IUCF). A Radiation Effects Research Station has been developed at IUCF which provides a convenient facility for these experiments[4]. At this station, the proton beam passes through a collimator, a secondary electron monitor (SEM), and a thin Kapton vacuum window into a short air gap where the detectors being tested are positioned. The beam spot at this point is as large as 7 cm in diameter. Considerable effort has been made to provide an accurate measure of the fluence incident upon the devices being tested. Before the irradiation, the SEM is calibrated by insertion of a remotely actuated beam stop/Faraday cup located between the SEM and the vacuum window. The calibration beam stop is removed and the intensity profile of the beam spot is measured by the exposure of GAFCHROMIC films at the target position. The films are then scanned photometrically into digitized profiles in the dosimetry computer. To perform the irradiation, the calibration beam stop is moved away and the SEM measures the beam current through the collimator and onto the target. The SEM currents and the information from the film are then used to compute the proton fluence. The irradiation is carried out under computer control, the beam stop being moved back into place automatically when the correct fluence is attained. This was the procedure adopted: irradiate detectors to a planned fluence, measure the leakage current, peak position, and resolution at 59.5 and 122.1 keV, repeat until the maximum fluence is reached. Irradiations began at the 1×10^8 p cm^{-2} fluence level and were increased to 5×10^9 p cm^{-2}.

It was planned that the detectors would remain in the brass test fixture for the irradiation and the measurement of the gamma-ray spectra. After the first irradiation, however, the brass became very radioactive, producing a background which interfered with the calibration sources. So in all subsequent tests, the CdZnTe detectors were removed from the fixture, wrapped and placed in a plastic box for irradiation, then removed from the box and placed in the test fixture for acquisition of spectra, 300 seconds live time.

Table 2 shows the peak position, resolution and leakage current at each step of the irradiation for the eV 2 mm detector. Figures 3 and 4 show the spectra of the calibration sources for the eV 3 mm detector before the irradiation and after a fluence of 5×10^9 p cm^{-2} for ^{241}Am and ^{57}Co. Table 3 shows the peak position, resolution and leakage current for the eV 3 mm detector. It is clear from the results that the peak position of gamma ray lines is shifted downward as a result of the irradiation.

Table 2. Summary of results for the eV 2 mm detector irradiation

	59.5 keV		122.1 keV		
Fluence (10^8 p cm^{-2})	Peak Channel	Resolution (keV FWHM)	Peak Channel	Resolution (keV FWHM)	Leakage Current (nA)
0	299	3.6	625	6.0	17
1	-----	-----	-----	-----	-----
2	-----	-----	-----	-----	-----
5	294	3.6	617	5.6	22
10	290	3.4	610	5.8	21
20	282	3.6	589	6.1	21
50	255	3.5	546	6.5	16

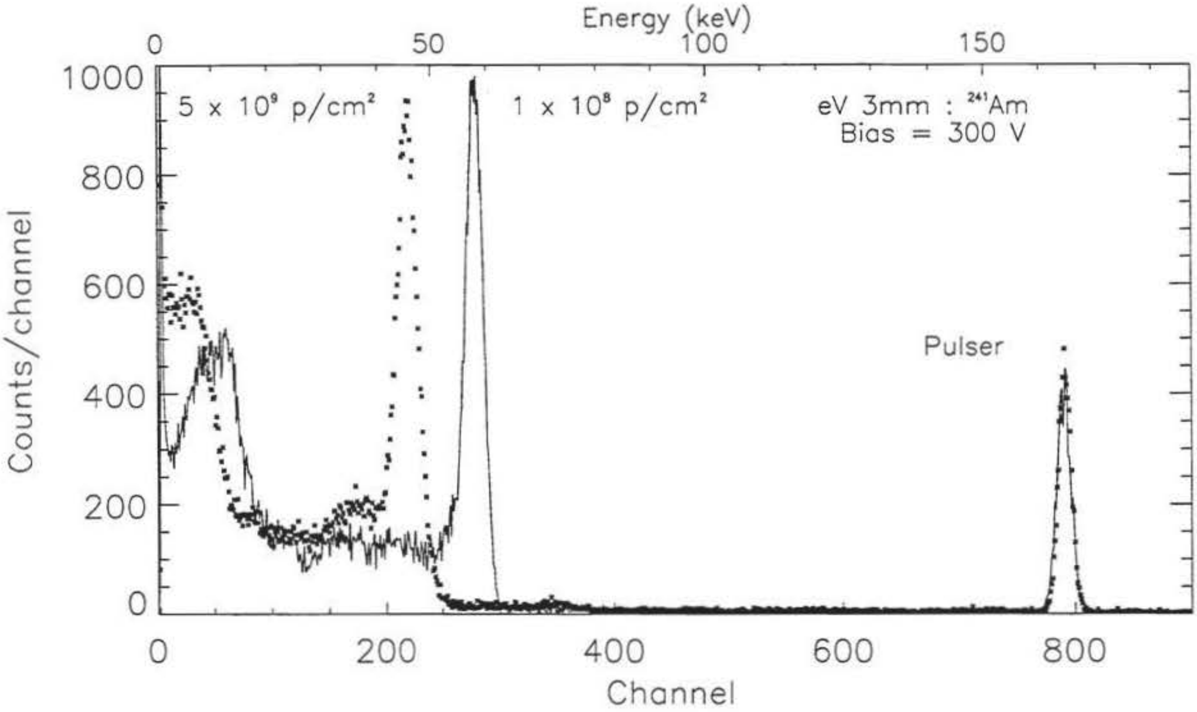

Figure 3. Spectrum of ^{241}Am for the 3 mm eV detector before and after irradiation

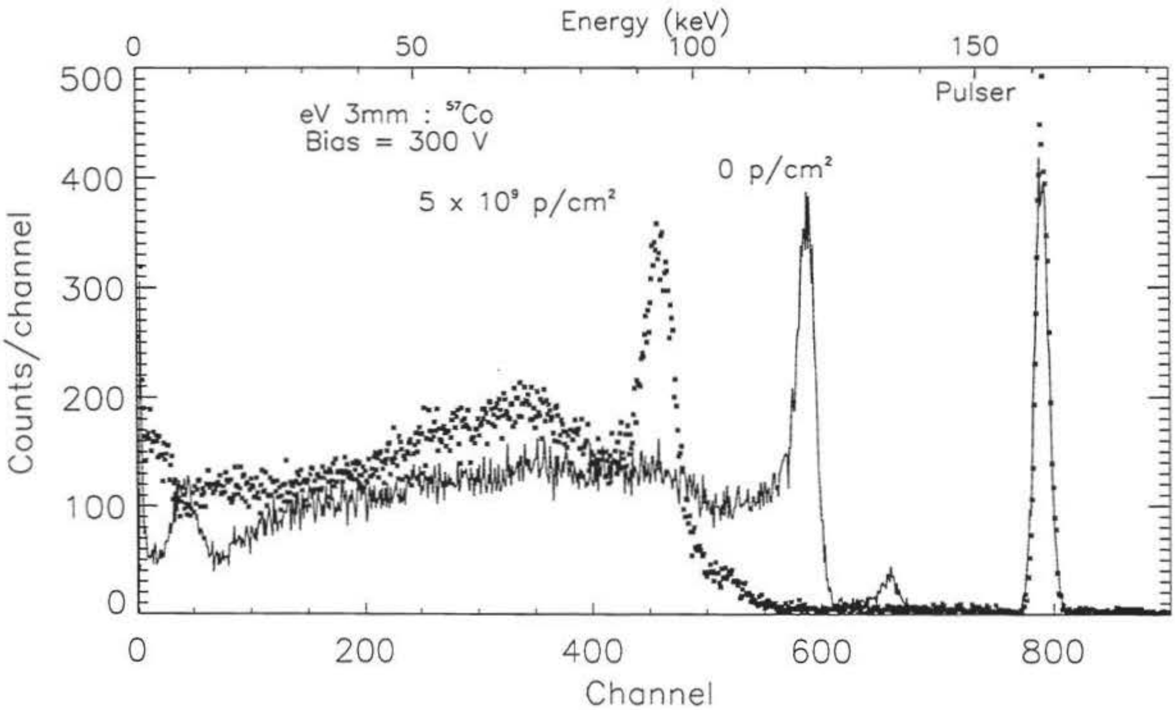

Figure 4. The spectrum of ^{57}Co for the 3 mm eV detector before and after irradiation

Table 3. Summary of results for the eV 3 mm detector irradiation

	59.5 keV		122.1 keV		
Fluence (10^8 p cm^{-2})	Peak Channel	Resolution (keV FWHM)	Peak Channel	Resolution (keV FWHM)	Leakage Current (nA)
0	280	3.2	588	3.9	13
1	279	3.6	584	4.3	15
2	277	3.6	581	4.0	15
5	274	3.6	575	4.0	15
10	270	4.1	561	4.3	14
20	256	4.3	542	5.9	14
50	221	6.2	460	9.2	11

The peak position shows a linear dependence on the fluence. The results can be interpreted as a decrease in the effective trapping length of the electrons. To verify this interpretation, the $\mu\tau$ values of the detectors were measured. The 59.5 keV peak position was measured as the bias voltage on the detector was increased. The peak position is proportional to the total charge collected at the electrode, Q, which is given by the equation for one carrier:

$Q = n_0 e(\lambda/d)(1-\exp(-d/\lambda)$, where $\lambda = E\mu\tau$

E = Electric field (V cm^{-1})
μ = mobility (cm^2 V^{-1} s^{-1})
τ = carrier mean life (s)
e = electron charge (C)
n_0 = number of electron-hole pairs created by gamma ray

The results of the $\mu\tau$ measurements are given in Table 4.

Table 4. $\mu\tau$ values before and after irradiation to 5×10^9 p cm^{-2} for the eV 2 mm and 3 mm detectors

	eV 2 mm	eV 3 mm
$\mu\tau$ before irradiation (cm^2/V)	6.6×10^{-3}	4.2×10^{-3}
$\mu\tau$ after irradiation (cm^2/V)	2.6×10^{-3}	1.3×10^{-3}

For charge deposited in a detector of thickness d at depth x from the cathode, the charge induced by both holes and electrons is[5]:

$$Q = n_0 e[(\lambda_e/d)(1- \exp(-(d-x)/\lambda_e) +(\lambda_h/d)(1- \exp(-x/\lambda_h)]$$

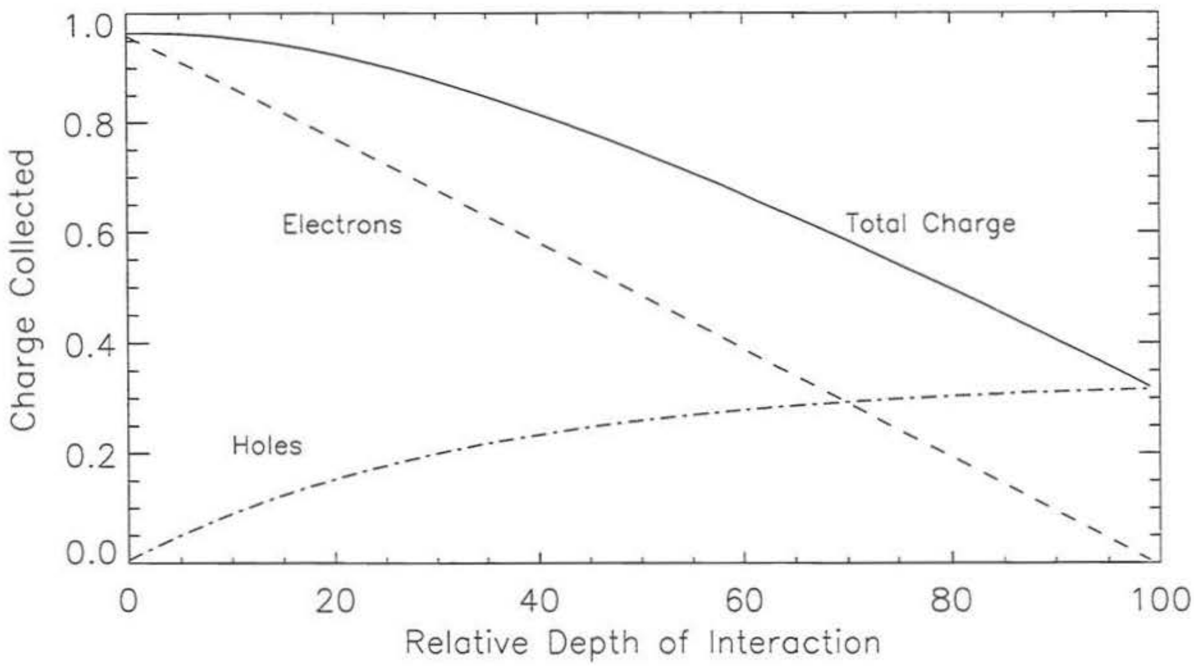

Figure 5. Charge collection in a 3 mm thick detector with $\lambda_e = 4$ cm and $\lambda_h = 0.1$ cm

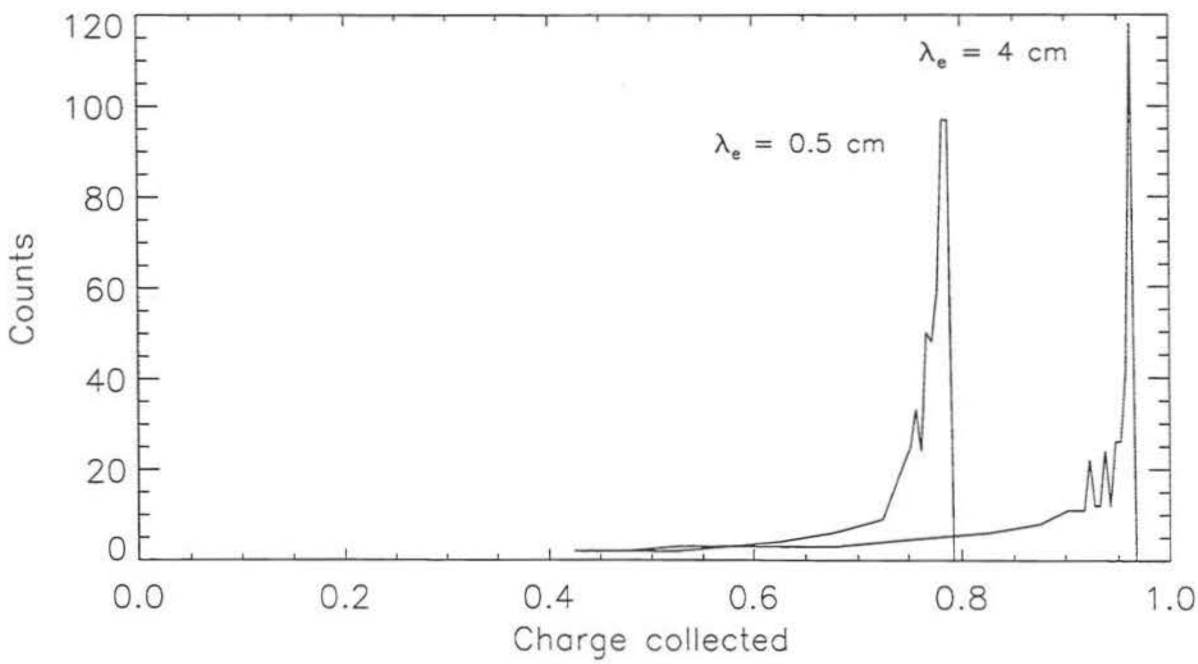

Figure 6. Comparison of calculated spectra for 122.1 keV for $\lambda_h = 0.1$ cm, $\lambda_e = 4$ cm and 0.5 cm

The charge collected for a 3 mm detector with λ_e = 4 cm and λ_h= 0.1 cm, is shown in Figure 5, along with the separate contributions from electrons and holes. A computer program has been written to calculate the spectrum for photon energies of 59.5 and 122.1 keV, using values for λ_e from 4 to 0.5 cm and for λ_h from 0.1 to 0.05 cm. Detector thicknesses of 0.3 cm and 0.2 cm were used, and the exponential absorption of the gamma rays in the detector was included. The program does not yet take into account ballistic deficit or various statistical processes; it is planned to add these features later. Results are shown in Figure 6 for λ_h = 0.1 cm and two values of λ_e, 4 cm and 0.5 cm. It is evident that a decrease in $\mu\tau$ for the electrons can account for the decrease in peak position seen in the radiation damaged detectors.

Charge collection in the Digirad array does not follow the model described above for the planar detectors. The Digirad array also showed radiation damage at 5×10^9 p cm^{-2}, but the peak position did not change linearly with the fluence. An anneal at 100 C for 16 hours brought the array back to its performance before irradiation.

CONCLUSIONS

Our accelerator experiments indicate that radiation effects will be important for instruments using CdZnTe in future space experiments. High energy protons produce electron traps which reduce the mobility lifetime product for the electron carriers. This results in a shift of gamma -ray peaks to lower pulse height and degraded energy resolution. Full performance can be restored by annealing the damaged detectors.

REFERENCES

1. W.A. Mahoney, J.C. Ling, and A.S. Jacobson, Radiation Damage of the HEAO C-1 Germanium Detectors, Nucl. Instrum. and Meth. 185, 449-458(1981).

2. M. Koenen, J. Brueckner, M. Koerfer, I. Taylor, H. Waenke, Radiation Damage in Large-volume n- and p- type High-purity Germanium Detectors Irradiated by 1.5 GeV Protons, IEEE Trans. Nucl. Sci. 42, 653-658(1995).

3. EXIST, MIDEX Proposal to NASA,1996.

4. C. C. Foster, S. L. Casey, P. Miesle, N. Sifri, A. H. Skees, and K. M. Murray, Opportunities for Single Event and Other Radiation Effects Testing and Research at the Indiana University Cyclotron Facility, NSREC'96 CONFERENCE. To be published in IEEE Trans. Nucl. Sci.

5. K.S. Shah, J.C. Lund,and F. Olschner, Charge Collection Efficiency in a Semiconductor Radiation Detector with a Non-constant Electric Field, IEEE Trans. Nucl. Sci. 37, 183-186(1990).